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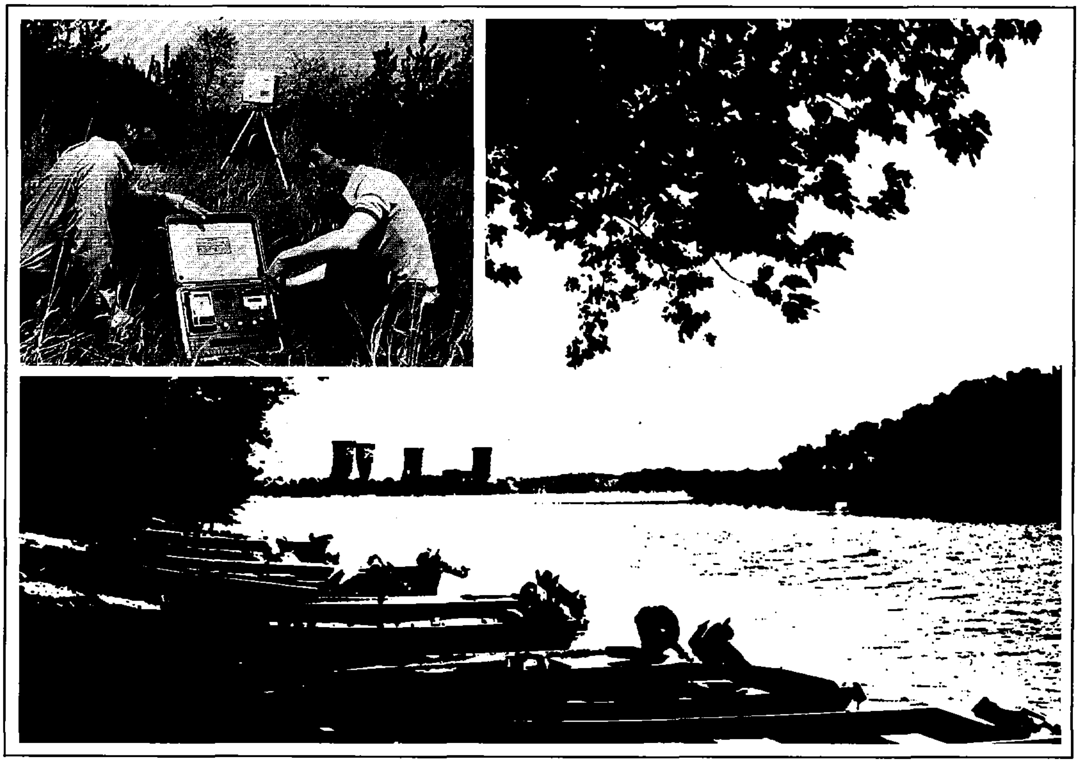
Radiation And Health Effects



A Report on the TMI-2 Accident and Related Health Studies

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RADIATION AND HEALTH EFFECTS

A Report on the TMI-2 Accident and Related Health Studies

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FOREWORD

Over the past seven years, considerable attention has been given to the accident at Three Mile Island Unit 2. Official investigations have been conducted, scientific and medical studies performed, and private surveys launched.

Much interest has been focused, in particular, on the question of whether the accidental release of radioactivity from the plant into the environment has affected the health of the more than two million people who reside within 50 miles of Three Mile Island.

In this report, GPU Nuclear Corporation, the operator of the TMI nuclear power plant, draws together much of what is known to date about the accident and its effects on human health. The report consolidates the results of a number of scientific studies into a single document. It explains how the radioactivity escaped, how it dispersed to the environment, the radiation doses received by people in the community and what health effects are to be expected from the radioactive releases.

We have been involved in the investigation of the accident at TMI-2 and have been closely associated with the cleanup as members of the TMI-2 Safety Advisory Board. We believe the report is accurate and reflects the information contained in the scientific studies of the accident.

This report should answer many questions and address concerns that some residents around TMI may have regarding their health and that of their families and friends. It should help them put their minds at ease and permit them to understand better the events of the accident and the real and potential health effects on the communities.

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SUMMARY

On March 28, 1979, the Unit 2 reactor at the Three Mile Island (TMI) Nuclear Station was severely damaged by an accident. Radioactivity was discharged to the environment resulting in a small amount of radiation exposure to the public. Continuing concerns by some members of the communities around TMI about the potential radiation-induced health effects prompted GPU Nuclear Corporation to examine the information gathered from the accident investigation in the context of our current knowledge of radiation and its effects on human health. Although this report deals with technical matters, the information is presented in a manner that can be understood by those who do not have scientific backgrounds.

This report is divided into three major sections. The first section provides an overview of the past 80 years of relevant research on the subject of radiation and its effects on human health. During that time, scientists and physicians throughout the world have studied hundreds of thousands of individuals exposed to radiation from medical and occupational sources and from nuclear weapons explosions. Epidemiologic studies of humans, such as the Japanese survivors of the atomic bomb, have established that following exposure to large doses of radiation, certain health effects, including cancer, can be observed.

Radiation-induced health effects from low doses of radiation, such as those associated with the TMI-2 accident, appear infrequently, if at all, and are identical and, therefore, indistinguishable from similar health effects which occur normally. For example, cancers induced by radiation are indistinguishable from those occurring spontaneously or normally. It is not possible, therefore, for scientists to determine directly whether radiation-induced health effects at low doses occur at all; such observations can only be inferred by statistical methods.

Radiation induced health effects from low doses of radiation, such as those associated with the TMI-2 accident, appear infrequently, if at all, and are identical and . . . indistinquishable from similar health effects which occur normally.

The second section of this report provides a brief description of the TMI-2 accident. Most of the radioactivity from the damaged fuel was prevented from escaping from the reactor plant into the environment. Radioactivity which was released into the environment consisted primarily of the noble gases xenon and krypton. Small amounts of radioactive iodine and trace quantities of several other radioactive elements also escaped into the environment. Radiation doses to humans and the environment were measured by radiation detectors and calculated from environmental samples. Nearly 10,000 samples of air, water, milk, fish, fruits, meat, soil and river sediment were analyzed and demonstrated that radioactivity released to the environment was small and will have no detectable impact on human health.

The accident was investigated and all available scientific data have been analyzed by a number of independent committees of experts, including the President's Commission (appointed by President Jimmy Carter), the Governor's Commission (appointed by Governor Dick Thornburgh) and committees representing several federal agencies (i.e., Nuclear Regulatory Commission, Department of Health Education and Welfare, Environmental Protection Agency, and Department of Energy), state governments, foreign countries and industry. There was general agreement among all these investigative committees that the radiation doses to the general public were small. Among the important findings, all of which have been published, are:

Section 2

- The highest possible whole-body dose to any one individual was less than 100 millirems (0.1 rem).
- The average whole-body dose to individuals within 10 miles of TMI was less than 8 millirems (0.008 rem).
- The average whole-body dose to individuals within 50 miles of TMI was less than 1.5 millirems (0.0015 rem).
- On the basis of these radiation doses, it can be concluded that the potential health effects, if any, would be so small as to be undetectable.

These radiation doses can be viewed in perspective when it is recognized that, in any given year, each person in the United States receives approximately 100 millirems (0.1 rem) of natural background radiation exposure. Medical and dental radiation for the average American contributes approximately an additional 90 millirems (0.09 rem) per year. The one-time radiation doses resulting from the radioactivity released during the TMI-2 accident, therefore, represent only a small fraction of the yearly radiation dose that all of us receive throughout our lives from natural background radiation.

The radiation doses to the general public were primarily due to the release of the radioactive but biologically inert noble gases, krypton and xenon. Other radionuclides, such as iodine, were released in barely detectable quantities. Because the radioactive gases readily dispersed into the atmosphere, exposure of people was transient and confined to individuals in the path of the plume.

The third section of this report reviews health studies which have been conducted on TMI-area residents between 1979 and 1985. Within months after the accident, the Pennsylvania Department of Health initiated studies which assessed possible radiation health effects among TMI area residents. Several of these studies evaluated potential health effects on pregnant women and their unborn children. Among the most extensive health studies was an analysis of cancer occurrence among all individuals living within 20 miles of TMI. Results of these health studies have been published and are available to the public.

For doses of radiation equal to those resulting from the TMI-2 accident, human health effects have never been detected in any population thus far studied.

To date, none of these studies has shown health effects to exist in excess of the normally expected incidence. This absence of measurable health effects is consistent with past scientific observations. For doses of radiation equal to those resulting from the TMI-2 accident, human health effects have never been detected in any population thus far studied.

We hope that this report will help to answer any lingering questions and address concerns that our neighbors might have regarding the TMI-2 accident and the potential health effects that might occur. We realize, however, that we cannot possibly address every individual concern, so if you have further questions, please feel free to write us at:
TMI Public Affairs Department, P.O. Box 480, Middletown, PA 17057.

James E. Hildebrand
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CURRENT KNOWLEDGE OF RADIATION HEALTH EFFECTS

SOURCES OF RADIATION

Mankind has lived with radiation and always will; there is no choice. Radioactivity has been a part of our planet since its creation. Even some of the atoms that constitute our bodies are radioactive; in fact, more than 7,000 atoms give off radiation in our bodies every second. Within that same second, about 300 cosmic rays from outer space pass through the body. Natural radioactivity in the soil, water, air and building materials also emits radiation. Table 1 summarizes the common sources of radiation and their average annual doses.

Section 3

Table 1
Sources and Doses of Radiation[5,21]

Natural		Man-Made	
Source	Radiation Dose (millirems/year)	Source	Radiation Dose (millirems/year)
Cosmic rays	42	Medical/Dental exposure	90
Building materials	35	Weapons fallout	5-8
Internal	28	Releases from nat. gas, phosphate mining, burning of coal, etc.	5
Ground	11		
		Consumer products	Less than 1
		Nuclear power plants	Less than 1
APPROXIMATE TOTAL	100	APPROXIMATE TOTAL	100

The average person in the United States receives about 100 millirems (0.1 rem) per year from natural background radiation sources. In some regions of the country, the amount of natural radiation is significantly higher. Residents of Colorado, for example, receive an additional 80 millirems (0.08 rem) per year due to the increase in cosmic and terrestrial radiation levels. In fact, for every 100 feet above sea level, a person will receive an additional 1 millirem (0.001 rem) per year from cosmic radiation. In several regions of the world, high concentrations of uranium and radium deposits result in doses of several thousand millirems (several rems) each year to their residents.

Recently, public attention has focused on radon, a natural radioactive gas produced as uranium and radium decay. These elements are widely distributed in trace amounts in the earth's crust. Unusually high concentrations have been found in certain parts of eastern Pennsylvania and northern New Jersey. Radon levels in some homes in these areas are hundreds of times greater than levels found elsewhere in the United States. The National Council on Radiation Protection and Measurements (NCRP) estimates that the average individual in the United States receives an annual dose of about 3,000 millirems (3 rems)[19] from natural radon. Because radon and its radioactive daughters emit alpha radiation, this dose is limited to the surface cells of the respiratory tract. Drinking water contains trace amounts of uranium and radium. Milk contains radioactive potassium.

In addition to such natural radiation, we are exposed to radiation from a number of man-made sources. The single largest of these sources comes from diagnostic medical x-rays, fluoroscopic examinations and radioactive pharmaceuticals. Some 160 million Americans receive medical or dental x-rays each year. The annual dose to an individual from such irradiation averages about 90 millirems (0.09 rem), about the same as that from natural radiation. Much smaller doses come from consumer products such as televisions, smoke detectors and fertilizers, nuclear weapons fallout and production of nuclear power and its associated fuel cycle.

Radiation such as x-rays, gamma rays and energetic subatomic particles (electrons, protons, neutrons, and alpha particles) can change the structure of molecules in body tissue by adding or removing electrons. The amount and distribution of altered molecules depends on the type of radiation. Unlike penetrating x-rays and gamma rays, charged particles, such as alpha particles and electrons, can only penetrate a short distance in tissue.

When we breathe or swallow radionuclides, their distribution within the body is not uniform. For example, radioactive iodine selectively concentrates in the thyroid gland, radioactive cesium is distributed throughout the body water and muscles, and radioactive strontium concentrates in bone. The total dose to organs by a given radionuclide is also influenced by the quantity and the duration of time that the radionuclide remains in the body, including its physical, biological and chemical characteristics. Depending on their rate of radioactive decay and biological elimination from the body, some radionuclides stay in the body for very short times while others remain for years.

HISTORICAL BACKGROUND

". . . it is fair to say that we have more scientific evidence on the hazards of ionizing radiation than most, if not all, other environmental agents that affect the general public."

Medical scientists have been studying ionizing radiation and its effects on human health for more than eight decades. The General Accounting Office reported in 1981 that there were more than 80,000 separate scientific studies of the health effects of radiation. The estimated cost of this research is about $2 billion. In fact, the National Academy of Sciences has stated that, ". . . it is fair to say that we have more scientific evidence on the hazards of ionizing radiation than most, if not all, other environmental agents that affect the general public."[16]

The first case of human injury reported due to radiation occurred shortly after Wilhelm Roentgen's discovery of x-rays in 1895. The early radiologists often used their hands to focus the primitive fluoroscopic equipment which exposed them to millions of millirems (thousands of rems) of radiation. As early as 1902, the first case of radiation-induced skin cancer was reported. In subsequent years, it was shown that physicians, x-ray technicians and radium handlers had cancer rates which were higher than normal.

The earliest efforts to set radiation standards were made by the Roentgen Society formed in 1916. By 1921, a newly formed British X-ray and Radiation Protection Committee was established to define the maximum tolerance dose. Additional guidelines on radiological protection were provided by the International Commission on Radiological Protection (ICRP), formed in 1928. Shortly thereafter, in 1929, the Advisory Committee on X-ray and Radium Protection was founded in the United States; this is now the National Council on Radiation Protection and Measurements (NCRP). ICRP and NCRP have the longest continuous experience in the review of radiation health effects and recommendations on guidelines for radiological protection and radiation exposure limits.

But their efforts have not been the only ones. In 1955, the United Nations created a Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to make yearly progress reports and to summarize reports received on radiation levels and effects on man and his enviroment. The National Academy of Sciences (NAS) formed a committee in 1956 to review the biological effects of atomic radiation (BEAR). A series of reports have been issued by this and succeeding NAS committees on the biological effects of ionizing radiation (BEIR), the most recent being 1980 (known as BEIR III). The NAS continues to review the health effects of ionizing radiation; the work of the fourth committee was begun in 1985.

These committees and commissions of nationally and internationally-recognized scientific experts have been dedicated to the understanding of the health effects of radiation by investigating all sources of relevant knowledge and scientific data and by providing guidance for radiological protection. Their members are selected from universities, scientific research centers and other national and international research organizations. The reports contain scientific data obtained from physical, biological, and epidemiological studies on radiation health effects, and serve as scientific references for information presented in this report.

HEALTH EFFECT STUDIES

Much of our current knowledge of the health effects of radiation comes from extensive laboratory animal experiments. Under laboratory conditions many crucial variables can be accurately controlled. These include, for example, the total dose, time interval and quality of radiation and the individual characteristics such as age, sex and health status.

While laboratory animal experiments serve as valuable models for human studies, there are limitations in drawing conclusions from biological effects observed in irradiated animals to potential health effects in humans. Thus, the most relevant studies are the epidemiological surveys that have focused on human populations who received radiation under a variety of conditions of intentional or inadvertent exposure. Most of these epidemiological studies involved population groups ranging from several hundred to more than 100,000 individuals. The most important surveys have involved the following groups:

- **Survivors of the Atomic Bomb and Nuclear Weapons Tests** - The most intensely studied human populations are the Japanese survivors of the atomic bombs in Hiroshima and Nagasaki. These people were exposed to radiation from the bombs and, subsequently, radioactive fallout. Studies have also been made of natives of the Marshall Islands who were accidentally exposed to fallout from nuclear weapons testing in 1954.

- **Medical Radiation** - Large doses of radiation were given to treat various health problems, such as ankylosing spondylitis, thymus enlargement, ringworm of the scalp, and breast cancer. Children whose mothers were irradiated during pregnancy have also been studied.

- **Radium Dial Painters** - Workers early in this century ingested radium-containing paint from luminous watches, clocks and aircraft instruments through a practice of "tipping" paint brushes with their lips.

- **Uranium Miners** - Early in this century, certain large mines in Europe were worked for pitchblende, a uranium ore. Lung cancer was highly prevalent among the miners as a result of the inhalation of large quantities of airborne radioactive dust particles. Studies have shown that the risk of lung cancer among these miners was at least 50 percent higher than that of the general population.

- **Radiologists** - Pioneer medical scientists and physicians using x-rays, unaware of the potential hazards, accumulated large radiation doses principally to their hands.

These and other populations, many of whom continue to be studied to add to our current understanding, provide reliable data on health effects resulting from large doses of radiation. Among radiation scientists, there is nearly complete agreement on the health effects and risks following such large radiation doses. What remains uncertain and controversial is the assessment of potential health effects which may result from small doses of radiation.

Central to this controversy is our inability to detect an increased incidence of cancer or other diseases resulting from exposure to small radiation doses, such as those from natural sources. Health effects from such low doses occur so infrequently, if at all, that they cannot be observed directly or detected statistically above what would be expected to occur spontaneously or normally in an otherwise unirradiated population.

Therefore, while scientists can predict the potential health effects of low-dose radiation with some uncertainties, it is well-recognized that the frequency of these effects is too small to measure directly. There is evidence that these very low dose levels may not be harmful.

The risk estimates that are calculated are determined by statistical analyses of health effects observed at high-dose levels; these effects have not been observed following exposure to very low levels.

Since we cannot detect health effects from low-dose radiation, nevertheless, for prudent radiation protection guidance we assume that health effects occur at a level proportionate to those that occur following high doses of radiation. It is generally agreed among radiation scientists that such estimates tend to overestimate the potential risk of radiation. The risk estimates that are calculated are determined by statistical analyses of health effects observed only at high-dose levels; these effects have not been observed following exposure to very low levels.

ACUTE RADIATION HEALTH EFFECTS

Radiation affects the individual cells that are the building blocks of the tissues and organs of the body. Although all cells can be affected by radiation, some are more sensitive to radiation injury than others. In general, the degree of sensitivity depends on the rate of cell division. Cells of the bone marrow, stomach lining and male reproductive tissues, for example, divide rapidly while brain cells do not. Rapidly dividing cells, in general, are more easily damaged than slower or nondividing cells. Cellular injury may involve a change in the nucleus that prevents the cell from dividing properly or not at all. For certain types of cells, whose primary function is to provide new cells by cell division, an inability to divide may result in short-term or acute health effects. These acute or early effects may appear within days or weeks after exposure to radiation. Such short-term health effects may result from external and internal radiation exposure of the whole body or selective tissues.

Acute health effects require radiation doses some thousands of times greater than those received from natural sources. Generally, a dose of at least 100,000 millirems (100 rems) to the whole body within a short time is required to cause even the mildest symptoms. An acute whole-body dose of more than 400,000 millirems (400 rems), in the absence of medical treatment, may be fatal in about half the individuals exposed. However, even such a large dose given in small amounts over a prolonged period of time allows the body's natural mechanisms to replace or repair damaged cells as it would following any injury.

Among the most sensitive cells are bone marrow cells, which produce red and white blood cells. These cells carry oxygen or protect against infections from viruses and bacteria. At radiation doses above 100,000 millirems (100 rems), increasing numbers of bone marrow cells fail to divide, which reduces the number of blood cells. This can lead to anemia, impaired blood clotting, hemorrhage and infection. Collectively, these signs and symptoms are called the bone marrow syndrome (see Table 2).

Health Effects from

	Bone Marrow Syndrome
Chief Determining Organ	Bone Marrow
Time for Onset	2-3 weeks
Dose Range	100,000 - 500,000 millirems (100 - 500 rems)
Death Incidence	100,000 - 200,000 millirems - None 0 - 70% for doses of 200,000 to 500,000 millirems
Time for Death to Occur	3 weeks to 2 months
Signs & Symptoms	Malaise, nausea, vomiting, fever, shortness of breath, reduction of blood cells
Major Underlying Tissue Effects	Reduction of bone marrow cells and marrow function, infection, hemorrhage, anemia

*Based on information taken from reference 36.

Table 2

Acute Radiation Exposure*

Gastrointestinal Syndrome	Skin Effects
Small intestine	Skin
3-5 days	hours - days
500,000 - 1,000,000 millirems (500 - 1,000 rems)	Greater than 300,000 millirems (300 rems)
70% to 100% for doses of 500,000 to 1,000,000 millirems	None
3 days to 2 weeks	—
Malaise, loss of appetite, nausea, vomiting, diarrhea, fever, dehydration, circulatory collapse, loss of body salts	Skin reddening, hair loss, blisters, ulcerations, sloughing
Depletion of intestinal cell lining, marrow damage, infection	Cell depletion, ulceration, skin sloughing

Radiation doses to the whole body in the range of 100,000 to 200,000 millirems (100 to 200 rems) may result in a limited amount of acute radiation illness, but will rarely be fatal. Doses of this magnitude were common among the Hiroshima and Nagasaki survivors as well as some residents of the Marshall Islands. The illness from radiation doses in this range does not present a serious medical problem in that most persons will suffer minor discomfort, some nausea and fatigue, while others may have no symptoms at all. Symptoms of mild nausea and loss of appetite may appear briefly but are transient and fully reversible in most cases.

Whole-body doses in the range of 200,000 to 500,000 millirems (200 to 500 rems) give rise to the bone marrow syndrome within 2-3 weeks following exposure. Early symptoms may include nausea and vomiting. Additional symptoms may include chills, fever, malaise, headache, fatigue and loss of appetite.

Radiation doses in excess of 500,000 millirems (500 rems) produce gastrointestinal symptoms. Cells that line the stomach and intestines absorb nutrients from food, water and minerals. In addition, these cells provide a natural barrier against bacteria that normally reside in the intestine. Nausea, vomiting, and diarrhea may appear within minutes to hours after exposure. These symptoms may subside after a day or two, only to reappear more severely a few days later. At that time, diarrhea, dehydration, ulceration and infection may lead to fluid and chemical imbalance in the body and thus circulatory collapse and death. For whole-body doses greater than 1,000,000 millirems (1,000 rems), death occurs within about 10 days following exposure.

The cells responsible for producing sperm in men and ova in women are among the more radiation-sensitive cells of the human body. Transient infertility has been observed at doses of less than 200,000 millirems (200 rems) and permanent sterility at doses in excess of 400,000 millirems (400 rems).

Radiation injury to the skin may cause physical changes which can readily be observed. Doses of 300,000 millirems (300 rems) usually cause reddening of the skin, which may occur within hours and last for a day or two. This reaction is largely caused by small blood vessels that dilate following the release of histamine-like substances. This form of skin reddening is similar to the reaction to sunlight or allergens. Larger doses are required to cause skin ulcerations, permanent loss of hair, reduction in skin thickness and changes in skin color which may occur after several weeks. When skin doses are the result of whole-body exposure to penetrating radiation, injury to the skin is accompanied by the other clinical symptoms. If the radiation consists of beta particles or low-energy x-rays which have a very limited ability to penetrate beyond the outer layers of the skin, even doses greater than 1,000,000 millirems (1,000 rems) are not considered to be life-threatening.

. . . acute health effects occur only at extremely high doses, . . . thousands of times higher than those from the TMI-2 accident.

These acute health effects occur only at extremely high doses, that is, doses thousands of times higher than those from the TMI-2 accident. Thus, it follows that the radioactivity released during the TMI-2 accident could not have been high enough to cause any of the acute health effects discussed later in this report.

DELAYED RADIATION HEALTH EFFECTS

Certain health effects may not appear for years or even decades after exposure to radiation. Such effects result from specific changes that occur in some cells or a single cell. Although these selective cellular changes occur rarely, when they do there is a possibility that the altered cell may develop into cancer. If the altered cell is a reproductive cell, there is a possibility of transmitting genetic defects to the progeny of irradiated parents. Also, a developing embryo or fetus could possibly suffer injury if a pregnant woman is exposed to radiation.

. . . genetic effects . . . and cancer can be caused by many chemical, physical and biological agents, many of which exist naturally in the environment.

For small doses of radiation, the likelihood that even a single cell will undergo such a selective alteration leading to cancer is extremely low. Furthermore, genetic effects, disturbances in growth and development of an embryo, and cancer can be caused by many chemical, physical and biological agents, many of which exist naturally in the environment. Thus, for even large doses of radiation, health effects can only be observed as small increases above the spontaneous incidence.

Genetic Effects

Genetic changes in the sperm or egg cells can result in ill-health appearing in future generations. The fertilized egg contains all of the genetic information necessary to produce the organs and tissues of a new individual. This information is carried in the cell's nucleus in small chromosomes, of which equal numbers are contributed by both parents. The chromosomes transmit the genetic information from one generation to the next.

The genetic material contained in the cell nucleus can be altered by a large variety of toxic agents, including heat, chemicals, and both natural and man-made radiation. Genetic mutations occur randomly in all plant, animal and human populations and are considered to be the primary mechanism for evolutionary changes in all species. Geneticists generally agree that most such mutations are harmful. Epidemiological studies have shown that about 11 percent of all people are affected by a genetic disease at some time in their lives.[16]

Laboratory studies of mice exposed to large doses of radiation for many generations have shown genetic effects. Studies of humans, however, have not yet produced reliable evidence for inheritable effects, such as developmental malformations, still births or neonatal deaths. It is difficult to measure most mutations because they are difficult to observe and are randomly distributed within a population group. Of the 35,000 children born to parents irradiated at Hiroshima and Nagasaki, – the average parental dose being 25,000 to 35,000 millirems (25 to 35 rems) – there has been no observable increase in genetic defects. Using all the information available, scientists have estimated that 100,000 to 200,000 millirems (100 to 200 rems) to each person in a large population would be required to produce genetic mutations equal in number to those occurring naturally in a non-irradiated population.

Of the 35,000 children born to parents irradiated at Hiroshima and Nagasaki. . . there has been no observable increase in genetic defects.

Radiation Effects on the Human Fetus

Studies on the embryo-fetus exposed in-utero have demonstrated that the human fetus is sensitive to low-dose radiation. Radiation injury to the human fetus may be expressed as congenital defects, mental retardation and leukemia. As regards the induction of mental retardation, *the fetus is most likely to be affected during the 8th to the 15th week* of pregnancy, an initial period when specific cells, including those of the brain, are undergoing crucial development. Although animal experiments have shown developmental health effects with the embryo-fetus for radiation doses as low as 5,000 to 10,000 millirems (5 to 10 rems), it is not possible to demonstrate with certainty that injury to a human fetus can be induced by such low doses. The evidence is based on the epidemiological studies of children born to women of Hiroshima and Nagasaki who were exposed to radiation in-utero. The atomic bomb studies have not associated doses below 25,000 millirems (25 rems) with developmental abnormalities of the newborn, such as central nervous system defects, skeletal abnormalities or reduced stature.

Pregnant women have been exposed to medical radiation for diagnostic medical purposes. There is no evidence that associates such low-dose exposure to growth and developmental abnormalities in human fetuses or young children. According to the medical evidence available today, the increased risk from doses less than 10,000 millirems (10 rems) for any individual is very small compared with the normal risk of developmental abnormalities in the newborn.

Childhood cancer studies among the Japanese exposed to radiation in-utero showed no significant excess of mortality from juvenile leukemia or other cancers.[11] Other studies predict that the risk of leukemia and other childhood cancers in children increases if the mother is exposed to diagnostic radiation to the abdomen during pregnancy. These data suggest that the incidence of leukemia among children from birth to 10 years of age in the United States could rise from 3.7 cases to 5.6 cases in 10,000 children if each child were exposed to 1,000 millirems (1 rem) of radiation before birth.[20] However, these surveys remain controversial. There has been some criticism that the original survey may be flawed by certain selection factors, particularly since many of the radiological procedures were requested by physicians for medical reasons, and the data depended almost exclusively on recall of past events by affected mothers.

The National Council on Radiation Protection and Measurements (NCRP) recommends that special precautions be taken to limit exposure of pregnant women who may be exposed to radiation as part of their job. The NCRP recommends that the expectant mother should not be exposed to more than 500 millirems (0.5 rem) during the entire gestation period.[18]

Radiation and Cancer

Next to heart disease, cancer is the leading cause of death in the United States. The American Cancer Society estimates that in 1986, about 930,000 people will be diagnosed as having cancer. In 1985, an estimated 462,000 Americans died of cancer. It is estimated that one person in three (about 30 percent) will develop cancer some time during their lives, of which slightly more than half will eventually die of the disease.[17]

. . . the prevalence of cancer depends on many risk factors, including race, sex, diet, lifestyle, health, occupation and personal habits.

Cancer is considered to be a group of diseases and more than 250 different forms have been identified so far in humans. Taken together, they affect nearly every human cell type. Studies indicate that the prevalence of cancer depends on many risk factors, including race, sex, diet, lifestyle, health, occupation and personal habits. However, among the most important risk factors is the age of the individual, particularly after the age of 40. Figure 1 illustrates the relationship of age and cancer incidence in the general population. The risk increases significantly at about age 20 and increases approximately 100 fold by age 80.

Contrary to common belief, cancer is not a new disease brought on by industrialization. In fact, researchers believe that the vast majority of cancer-causing agents are of natural origin. Natural cancer-causing agents can be found in most foods which make up the human diet.[3] A variety of mold, for example, which frequently contaminates food such as corn, grain, nuts, bread, cheese and fruits has been identified as a major cause of liver cancer. Microrganisms, such as viruses, are also known to cause cancer.

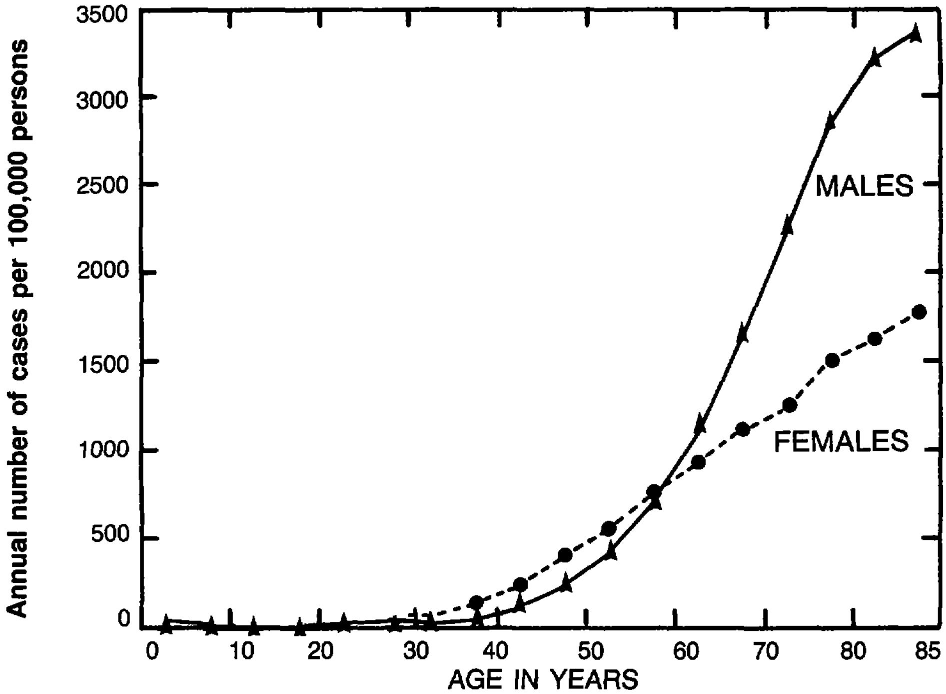
. . . researchers believe that the vast majority of cancer-causing agents are of natural origin.

In addition to an abundance of natural cancer causing agents, there are numerous man-made agents, including radiation, which can produce cancer. Tobacco smoking is without a doubt a major and well-understood risk, causing about 30 percent of all cancer deaths, including lung, larynx, and possibly bladder and breast cancer, as well as 25 percent of the fatal heart attacks in the United States.

The evidence for radiation-induced human cancer comes largely from population studies of three groups of people: (1) persons exposed to atomic bomb radiation; (2) persons exposed to medical radiation; and (3) persons exposed to radiation as part of their occupation. Collectively, these groups represent hundreds of thousands of individuals.

Interpreting epidemiological data requires an understanding of the disease process as it affects large populations, together with the statistical techniques used in the interpretation of data. Radiation-induced cancers may not appear for years or decades after exposure. This time delay between exposure to a cancer-causing agent and the clinical observation of a cancer is called the latency period. Human leukemias, for example, may not appear for two to five years after exposure; solid-tumor cancers, such as those of the lung or breast may not be evident for 10 years or more. Long latency periods, therefore, make the investigation of cancer-causing agents difficult. Many years of observation are required for reliable conclusions.

Figure 1
Cancer Incidence at Different Ages In the United States[37]



A second difficulty in the analysis of human data arises from the fact that cancers induced by radiation are indistinguishable from those arising spontaneously or those caused by other carcinogens. Physicians and pathologists cannot determine, based on tissue type, whether certain lung cancers, for example, are caused by radiation or by cigarette smoking, air pollutants, chemicals or other cancer-causing agents. The ability to detect the common cancers caused by any specific agent is, therefore, limited to statistical analyses. These statistical methods rely on the fact that the incidence of various cancers in a given population can be predicted with reasonable accuracy. For a sufficiently large group of people who have received radiation exposure, an incidence of cancers above the expected level would suggest that radiation was a possible cause for the excess number of cancers, but it would not identify radiation as the cause of a cancer for any specific individual.

Epidemiological studies of people who were exposed to relatively high doses of radiation (greater than 50,000 millirems or 50 rems) have shown a causal relationship between radiation and an increased cancer incidence. Studies of 82,000 Japanese survivors of the atomic bomb have provided valuable information on latency periods, the types of cancers associated with radiation and the doses of radiation required to induce an excess incidence of cancer. Based on reported location at the time of the blast and other factors, dose estimates have been calculated for 97 percent of these survivors.

Although radiation doses varied from thousands to hundreds of thousands of millirems (rems to hundreds of rems), the average whole-body dose has been estimated to be between 25,000 and 30,000 millirems (25 to 30 rems). Table 3 summarizes cancer mortality among atomic bomb survivors.

Table 3

Radiation-Induced Cancer Among Atomic Bomb Survivors Through 1978[12]

• 82,000	Survivors (a group selected in 1950)
• 23,500	Total Number Deceased
• 4,800	Cancer Deaths From All Causes
• 250	Cancer Deaths Attributed to Radiation

Different cells and tissues of the body are affected by radiation in different ways. Thus, some cancers are more frequently linked to radiation than others. On a relative basis, breast cancer, thyroid cancer and leukemia occur at a higher rate among people exposed to whole body radiation than they do among the general population. A moderately increased incidence occurs for lung, pharynx, pancreas, digestive tract and lymph node cancers.

Other cancers have a low induction rate or correspond to tissues not known to be affected by radiation. Although these cancers occur frequently in the normal population, to date they have not been observed in excess to their normal incidence among individuals exposed to radiation. This implies that the sensitivity to radiation induction of these cancers is either extremely low or is absent (see Table 4).

Leukemia was the first type of cancer to appear in excess in the Japanese survivors of the atomic bombs. The first cases began to appear in the late 1940's and peaked about five to nine years after exposure. Initial increases in breast, thyroid, and lung cancers were seen in the mid to late 1950's. A statistical excess increase for other cancers required even longer periods: stomach (about 15 years), urinary tract (about 20 years) and colon (more than 20 years). Some cancers, such as those of the urinary tract, were not seen at increased rates except in survivors who received radiation doses of more than 100,000 millirems (100 rems). Some cancers, including chronic lymphocytic leukemia, cancer of the cervix, and Hodgkin's disease, have not been observed for even high doses of radiation.

Table 4

Sensitivity of Various Tissues to Radiation-Induced Cancer[16]

Site or Type of Cancer	Spontaneous Incidence of Cancer*	Relative Sensitivity to Radiation Induction of Cancer
Major radiation-induced cancers		
Female breast	Very high	High
Thyroid	Low	Very high, especially in females
Lung (bronchus)	Very high	Moderate
Leukemia	Moderate	Very high
Alimentary tract	High	Moderate to low
Minor radiation-induced cancers		
Pharynx	Low	Moderate
Liver and biliary tract	Low	Moderate
Pancreas	Moderate	Moderate
Lymphomas	Moderate	Moderate
Kidney and bladder	Moderate	Low
Brain and nervous system	Low	Low
Salivary glands	Very low	Low
Bone	Very low	Low
Skin	High	Low
Site or tissues in which magnitude of radiation-induced cancer is uncertain		
Larynx	Moderate	Low
Nasal sinuses	Very low	Low
Parathyroid	Very low	Low
Ovary	Moderate	Low
Connective tissues	Very low	Low
Sites or tissues in which radiation-induced cancer has not been observed		
Prostate	Very high	Absent†
Uterus and cervix	Very high	Absent†
Testis	Low	Absent†
Mesentery and mesothelium	Very low	Absent†
Chronic lymphatic leukemia	Low	Absent†

* Spontaneous incidence of cancer refers to the relative frequency of naturally occurring cancers. Thus, cancer of the uterus, cervix and prostate occur frequently in a normal population, whereas cancers of bone or connective tissues occur rarely.

† The sensitivity to radiation induction of these cancers is either extremely low or is absent.

CANCER RISK ESTIMATES

Based on the epidemiological studies of large populations exposed to radiation, scientists can estimate how many people are likely to develop specific types of cancers. The probability of getting cancer from any cause is expressed in terms of risk coefficients (the number of cases expected per million people per unit of dose). Table 5 shows the radiation risk values for several types of cancer as estimated by the ICRP, the UNSCEAR and the BEIR III Report of the National Academy of Sciences. For example, the ICRP estimates that for one million people, each exposed to 1,000 millirems (1 rem) of radiation, there could be 20 radiation-induced leukemia fatalities. Risk values established independently by the three committees are in close agreement. It should be recognized that these estimates, based primarily on a linear response from high doses downward to low doses, are considered to be overestimates of risk to exposure to low-LET radiations, such as x-rays and gamma rays, and that the epidemiological data and analyses do not exclude zero cases as a lower bound.

Section 3

Table 5

Estimates of Lifetime Cancer Mortality by Anatomical Site Per Million People Exposed to 1,000 Millirems (1 Rem) Each*

Type of Cancer	ICRP	UNSCEAR	BEIR III
Leukemia	20	15-25	22
Lung	20	25	28
Breast	13	30	11
Bone	5	2-5	0.5
GI tract	–	25	19
Thyroid	5	5-15	7
Other	50	25	31
APPROXIMATE TOTAL	110	120	120

To understand what these figures mean, recall that the American Cancer Society estimates that about 30 percent of all Americans will develop cancer at some time in their lives from all possible causes (e.g., smoking, food, alcohol, air pollutants, etc.). Thus, in any normal population of 10,000 people, about 3,000 can be expected to develop cancer. If that same group were to receive 1,000 millirems (1 rem) of radiation, three more might develop cancer, of which one or two may be fatal.

. . . about 30 percent of all Americans will develop cancer at some time in their lives from all possible causes (e.g. smoking, food, alcohol, air pollutants, etc.).

* Taken from references 10, 16 and 39.

These three cancers could occur in addition to the 3,000 expected normally for a total of 3,003 cases. This means that a dose of 1,000 millirems (1 rem) to each of 10,000 individuals increases the cancer rate by only three one-hundredths of one percent (an increase from 30 percent to 30.03 percent). Thus, a lifetime dose of 10,000 millirems (10 rems) may increase the chance of cancer from 30 percent to 30.3 percent and a lifetime dose of 100,000 millirems (100 rems) may increase that chance by 3 percent (30 to 33 percent).

Risks from Low Radiation Doses

Most estimates of the number of cancers caused by radiation have relied on epidemiological studies where doses were generally more than 50,000 millirems (50 rems). In such studies, the long-term effects were observed as a higher incidence of cancer for a particular group of individuals than one would normally expect. When individual radiation doses are less than 10,000 millirems (10 rems), the dose is too small to detect any statistical excess cancers in the presence of naturally occurring cancers.

Estimates of health effects for low-level radiation are made by assuming that the frequency of risks observed at high doses can be proportionately related to corresponding low radiation doses. The estimates also assume that there is no threshold dose below which radiation will cause no cancers. This linear, no-threshold hypothesis assumes that for any dose, no matter how small, there is some correspondingly small risk even if it cannot be measured. Most scientists believe that the linear no-threshold relationship overestimates the health risk for small doses of low-LET (x-rays and gamma rays) radiation.

The linear, no-threshold hypothesis can be illustrated by the following example. For a group of 10,000 people, we expect about 1,800 to die of cancer from all causes. If each person were exposed to 100,000 millirems (100 rems) of radiation, then we can expect an additional 100 cancer deaths for a total of 1,900. This would be a sufficiently large increase to be readily detectable in an epidemiological study. But it would not be possible to distinguish which 100 of the 1,900 cancer cases were caused by radiation.

. . . estimating the health risk for low doses of radiation cannot be done directly, but can only be estimated . . . from cancer data observed at high doses . . .

Further, consider another group of 10,000 and reduce the exposure to 1,000 millirems (1 rem) each. This may result in only one additional fatal cancer, if any, for a total of 1,801. It is apparent that this one possible additional cancer death could have occurred normally or been caused by some factor other than radiation. In this case, the additional one death is too small a number to be statistically significant. Thus, estimating the health risk for low doses of radiation cannot be done directly, but can only be estimated statistically by extrapolating from cancer data observed at high doses into the low-dose region where cancer data are not available.

This uncertainty applies to small doses of other cancer-causing agents as well. We know, for example, that cigarettes and ultraviolet radiation cause cancer. Thus, for people who are lifetime smokers or who spend much of their time outdoors in the sun, the excess risks of lung or skin cancer are readily measured. A more difficult task would be to determine the risk of these cancers for people who smoke only a few cigarettes or who spend only a limited time in direct sunlight.

An illustration of the uncertainties for low-dose risks may be provided by the following relationship of lung cancer to cigarette smoking. Scientific studies have established that an additional 100 people will die of cancer out of 10,000 who smoke four cigarettes per day for many years.[17] Using the linear no-threshold dose-response model commonly applied to establish radiation risk, one additional death would be expected if each of these 10,000 only smoked one cigarette per month. This implies that 1,000 millirems (1 rem) of radiation has about the same cancer risk as smoking one cigarette per month since, as indicated above, one additional cancer death could result from 10,000 people being exposed to 1,000 millirems (1 rem) each.

THE TMI-2 ACCIDENT

FUNDAMENTALS OF REACTOR DESIGN

To understand what happened at the Three Mile Island Unit 2 nuclear power plant on the morning of March 28, 1979, it is necessary to know something about the design of the nuclear reactor. TMI-2 is a pressurized water reactor. The reactor has three independent cooling loops. Heat generated by the fission process within the reactor fuel core is transferred to circulating water of the primary loop. Water in the primary loop is kept from boiling by keeping it under high pressure (about 2,200 pounds per square inch).

Heat from the primary loop is transferred to the secondary loop by means of two steam generators. Water in the secondary loop boils to produce steam which expands, turns the turbine, spins the generator, and produces electricity. The steam, after passing through the turbine, is condensed back to water by a third separate loop which circulates water between the condenser and the cooling towers.

The TMI-2 reactor has five independent barriers that confine radioactive materials given off by the reactor fuel as it heats the water. Under normal operating conditions, essentially all radioactivity is contained within the first two barriers.

The ceramic uranium fuel pellets provide the first barrier. Most of the fission products are either trapped or chemically bound in the fuel where they remain. However, a few fission products which are volatile or gaseous at normal operating temperatures may not be contained in the fuel.

The second barrier consists of zirconium alloy tubes that resist corrosion and high temperatures. The fuel pellets are contained within these tubes. There is a small gap between the fuel and the cladding, in which the noble gases and other volatile radionuclides collect.

The primary coolant water is the third barrier. Many of the fission products, including radioactive iodine, strontium and cesium are soluble and are retained in water in an ionic (electrically charged) form. These materials can be removed in the purification system of the reactor. However, krypton and xenon do not readily dissolve in the coolant, particularly at high temperatures. Krypton and xenon collect as a gas above the coolant when the water is depressurized.

The fourth barrier consists of the reactor pressure vessel and the steel piping of the primary coolant system. The reactor pressure vessel is a 36-foot high tank with steel walls about nine inches thick. It encases the reactor. The remainder of the primary coolant system includes the pressurizer, steam generators and associated piping. This system provides containment for radioactivity in the primary coolant.

The reactor building (or containment building) provides the fifth barrier. It has steel-lined thick concrete walls that enclose the reactor pressure vessel and the primary coolant system.

During the TMI-2 accident, radioactivity was released to the environment when radioactive liquids were pumped from the reactor building to the auxiliary building. Even though primary coolant was transported to the auxiliary building, only certain radionuclides escaped into the environment for the following reasons: (1) radioactivity in the primary coolant is readily contained; (2) only radionuclides that leave the primary coolant water as a gas or vapor or are carried in steam can be discharged as airborne effluents; (3) prior to environmental discharge, the air in the reactor and auxiliary buildings is passed through high efficiency and charcoal filters which remove particulates (e.g., cesium, strontium, and alpha-emitting radionuclides) and iodine respectively; and (4) the most likely radionuclides to escape into the environment are krypton and xenon. Because these radioactive gases are chemically inactive, which means that they do not bind to other chemical elements, they are not removed by mechanical or chemical filtration. However, simply "holding" them for a period of time reduces the amount discharged since many radioactive forms of krypton and xenon exist for only short periods of time before they cease to be radioactive.

The radioactive materials released to the environment during the accident were those that were released from the damaged fuel and transported in the coolant to the makeup and purification system in the auxiliary building. The noble gases and radioactive iodines, because of their volatile nature and large concentrations, were the primary radionuclides available for release to the environment from the auxiliary building.

CONTRIBUTING EVENTS OF THE ACCIDENT

At approximately 4:00 a.m. on March 28, 1979, a malfunction occurred to components that maintain the flow of coolant water to the steam generators in the secondary loop. This resulted in a loss of ability to remove heat from the primary loop. Thus, most of the heat generated by the reactor remained in the reactor vessel and primary loop. This caused the coolant water temperature and pressure to increase rapidly. This, in turn, caused a relief valve on the pressurizer to open. Steam and water were discharged to the reactor coolant drain tank located in the basement and equipped with a pressure-limiting rupture disc.

A key factor in the accident was that the relief valve failed to close when pressure returned to normal. Water continued to be discharged through the open relief valve into the drain tank. As the water level fell, the fuel became exposed resulting in intense heat causing fuel damage.

So much water and steam were discharged through the relief valve that the storage capacity of the drain tank was quickly exceeded, causing the rupture disc to burst and discharge some 250,000 gallons of radioactive coolant into the reactor building sump and basement. Radioactive coolant water in the reactor building sump was automatically pumped into the auxiliary sump tank in the auxiliary building. Since this tank was already about half full, much of the water spilled into the auxiliary building, which was not designed to contain radioactive material. This liquid did not contain significant amounts of radioactivity, however, because major fuel damage did not occur until about two hours later.

After fuel damage occurred, radioactive materials were transported through the primary coolant system via the letdown line to the makeup and purification system in the auxiliary building. Because this liquid is a stream of primary coolant directly from the reactor, it contained significant amounts of radioactivity. As a result of liquid leaks in the makeup and purification system, large amounts of radioactive material were released into the auxiliary building. No longer held under pressure, krypton, xenon and other volatile radionuclides evolved from the water into the auxiliary building atmosphere.

RADIOACTIVITY RELEASED TO THE ENVIRONMENT

During the accident, approximately 50 percent of the noble gases and particulate cesium, 30 percent of the iodine and small quantities of other fission products were released from the damaged fuel into the primary coolant water. Before being released into the environment, the small amount of the airborne radioactivity released to the reactor building was filtered and monitored. The high efficiency filtration system in the auxiliary and fuel handling buildings was designed to remove more than 99 percent of radioactive cesium, strontium and alpha-emitting radionuclides. In addition to mechanical filtration, ventilated air in these buildings was also passed through multiple charcoal filters, which chemically removed 90 to 95 percent of the radioactive iodine. However, neither the mechanical filter nor the charcoal absorbers were designed to prevent the discharge of the chemically inactive krypton and xenon gases which escaped to the environment.

There were a number of pathways by which radioactivity other than noble gases was discharged through the TMI-2 stack. These pathways permitted small quantities of radioactive iodine, cesium, strontium, and alpha-emitting radionuclides to be released because some airborne radioactivity bypassed the building ventilation filtration system. Some of the discharged primary coolant water was pumped into a number of holding tanks in the auxiliary building. Noble gases evolved from coolant water contained in the holding tanks. Relief valves on these tanks, which were set at relatively low pressures, opened because of pressure produced by the noble gases. Noble gases and small quantities of several other radionuclides flowed through these relief valves in piping which bypassed the filtration system and discharged directly to the TMI-2 stack.

By analyzing the radiation monitors and filter media, it has been possible to measure the quantities of radioactivity released to the environment (Table 6). These measurements were supported by analyses of air, soil and water samples taken from various points outside the TMI-2 plant.

Table 6

Airborne Radioactivity Released to the Environment During the TMI-2 Accident

	Quantity (Curies)[13]	Half-Life
Noble Gases		
xenon-133	8,300,000	5.3 days
xenon-133m	170,000	2.3 days
xenon-135	1,500,000	9.1 hours
xenon-135m	140,000	15.6 minutes
krypton-85	49,000[7]*	10.8 years
krypton-88	61,000	2.8 hours
Radioactive Iodines		
iodine-129	0.000003[6]	millions of years
iodine-131	less than 30[27]	8.0 days
iodine-133	4	20.3 hours
Radioactive Cesiums		
cesium-134	0.00001	2.0 years
cesium-136	0.0000003	13.7 days
cesium-137	0.00004	30.0 years
cesium-138	0.00002	32.2 minutes
Radioactive Strontiums		
strontium-89	0.00006	52.7 days
strontium-90	0.00006	27.7 years
Activation Products		
tritium	147	12.3 years
cobalt-58	0.0004	71.3 days
cobalt-60	0.00009	5.3 years
Alpha-emitting Radionuclides		
gross alpha	0.00008	thousands of years

*This includes the 1980 reactor building purge.

Monitoring of Airborne Radioactive Pathways

All stack releases (filtered and unfiltered) are routinely monitored for radioactivity. In addition, other monitors positioned in the ventilation flow path evaluate filter performance and measure airborne radioactivity passing through filters in the auxiliary, fuel handling and reactor buildings.

Radioactivity that leaks from the primary to the secondary loop is measured at the condenser, where steam is converted to water again. This is where noble gases would most likely be detected.

Extremely sensitive monitors in the stack are designed to measure the small quantities of radioactive noble gases, iodine and particulates leaving the stack under normal operating conditions. Radiation doses resulting from such releases are small and do not present a health risk to the public. During the accident, radioactivity leaving the stack exceeded the capacity of the monitors due to noble gases. However, area monitors nearby were concurrently measuring radiation. Comparing figures from the recorded data on the two sets of monitors allowed scientists to devise a ratio to determine effluent releases. The validity of this computational method for determining environmental releases was subsequently supported by environmental monitoring and sampling.

Noble gases

Of the radioactivity released during the time of the accident, the most abundant radionuclides were those of the noble gases xenon and krypton. The best estimate of the total amount of noble gas discharged to the environment is 10 million curies, which represented about 0.8 percent of the total inventory in the reactor core. Additionally, about 44,000 curies of krypton-85 were released to the environment in June - July, 1980. However, this release of activity was approved by the NRC and Pennsylvania Governor Dick Thornburgh following a thorough evaluation by a task group of the National Council on Radiation Protection and Measurements.[15]

Iodine

Although there are 26 different isotopes of radioactive iodine produced in a nuclear reactor, after a period of one to two days only the longer-lived iodine-131 is of environmental and human health concern. Most of the other isotopes of iodine pose little or no threat to human health or the environment because they either have a very short half-life or are produced in negligible quantities. For example, iodine-129 remains radioactive for several million years; however, it has been calculated that at the time of the accident, there was only 0.217 curie of iodine-129 in the reactor vessel. It is estimated that only about 0.000003 curie of iodine-129 was released to the environment. Environmental releases of radioactive iodine originated as airborne releases in the auxiliary and fuel handling buildings. Although this air is filtered, small quantities were discharged via the stack. Estimates of radioactive iodine released were based on analyses of charcoal cartridges from the building ventilation filters.

Charcoal filter cartridges were routinely changed and analyzed for radioactivity by at least two independent laboratories. Of the 129 charcoal cartridges collected during the time of the accident, only one cartridge remains unaccounted for with several being mislabeled. To compensate, estimates of released iodine are given as a range of about 15 to 30 curies for iodine-131 and about 3 to 4 curies for iodine-133.

Particulates and Tritium

Hundreds of radionuclides are created during the process of generating electricity in a nuclear reactor. However, because of short life spans and chemical properties, the overwhelming majority of radionuclides remains in the coolant water and is not released into the environment. For those that do become airborne, the high-efficiency air filters reduce their discharge to the environment.

Analyses of airborne samples showed that about 147 curies of tritium were discharged to the environment from the stack during the accident.

Although sizeable quantities of radioactive cesium and strontium existed in the fuel, their physical-chemical behavior prevented their release to the environment. Laboratory analyses of particulate filters indicated releases of only about one ten-thousandth of one curie (0.0001 curie) of strontium and about seven one hundred-thousandths of one curie (0.00007 curie) of cesium.

Activation products and many alpha-emitting radionuclides are produced in the reactor. Because the TMI-2 reactor was relatively new and had only been in operation about three months, only limited quantities of activation products and alpha-emitting radionuclides existed at the time of the accident. Their release to the environment was restricted by their own physical-chemical properties and by filters. The results of gross alpha analyses indicate that about eight one hundred-thousandths of one curie (0.00008 curie) was discharged via the TMI-2 stack to the environment.

Liquid Pathways, Monitoring and Radioactive Effluents

Radioactive water released during the accident to the auxiliary, fuel handling and reactor buildings has been processed and is stored in tanks on Three Mile Island. The only releases of radioactive materials in liquid form were via the industrial waste treatment and filter systems. These systems normally collect non-radioactive water from various sumps. The water is filtered and discharged to the Susquehanna River via a single discharge point, which is continuously monitored for radioactivity. Because various tanks in the auxiliary building had overflowed, slightly radioactive water collected in some sumps was subsequently pumped to these systems. The industrial waste treatment system also processed radioactive water from the turbine building sump.

Small leaks in the steam generators allowed radioactive materials in the primary coolant to contaminate the TMI-2 secondary system. Small quantities of steam leaked from the turbine and condensed in the turbine building sump. That water was then pumped to the industrial waste treatment system. Studies indicate that no unmonitored water was released and that the monitor at the discharge point never reached a level sufficient to trigger an alarm.

At the time of the accident, Three Mile Island's undamaged Unit One reactor had just been refueled. Water from that reactor was being treated and discharged, a common procedure during refueling operations. From March 28 through April 30, 1979, water discharged to the river included 11 curies of tritium, 0.3 curie of iodine-131 and a total of 0.05 curie of other radionuclides. The only radionuclide identified in liquid samples that was directly attributed to the accident was iodine-131. The small amount of radioactive material released from TMI-1 at that time did not exceed release limits established by the Nuclear Regulatory Commission. Federal effluent limits are set at low levels to ensure the health and safety of the public.

ENVIRONMENTAL MONITORING AND RADIATION DOSE ASSESSMENT

The Nuclear Regulatory Commission (NRC) is the federal agency that oversees the operation of nuclear power plants. It requires plant operators to develop a comprehensive surveillance program that monitors all radioactive releases to the environment and provides information on their potential effect on human health and the environment. Prior to the TMI-2 accident, GPU had implemented a radiological environmental monitoring program. Under this program, more than 900 separate samples were analyzed annually from air, milk, fish, fruits, vegetation, meat, soil, water and river sediment. The analyses were used to assess the dispersion of radionuclides resulting from normal or accidental releases into the environment. In addition, radiation dosimeters (known as thermoluminescent dosimeters or TLD's) positioned around TMI measured radiation doses to humans, animals and plants.

Proven computer models are also used to calculate the dispersion of radioactivity and resultant radiation exposures to the environment and human population. Such calculations, which are also used to confirm environmental sampling and TLD data, take into account the amount of radioactivity released together with the prevailing weather conditions, such as temperature, wind speed and direction, precipitation and upper atmospheric conditions. This information is obtained by sensors located on a tower at the northwest section of TMI. Meteorological data are generated every 10 seconds and averaged over a 15-minute period before data are sent to a computer. The TMI meteorological station, which was in operation at the time of the accident, recorded actual data for the calculated values of radionuclide dispersion and radiation dose.[40]

Following the TMI-2 accident, environmental monitoring was greatly expanded. GPU performed 9,700 analyses of 5,500 environmental samples taken during 1979. In addition, the Pennsylvania Bureau of Radiation Protection, U.S. Department of Health and Human Services (HHS), Environmental Protection Agency (EPA), Department of Energy (DOE) and the NRC took samples and analyzed them for radionuclides. Also, researchers and officials from several universities and health departments of adjacent states helped analyze the data and monitored radiation levels. The EPA presented the data from more than 10,000 samples in a comprehensive report to the President's Commission on the Accident at Three Mile Island.[38]

Results of Environmental Sampling

Radionuclide analyses and respective dose estimates were obtained from milk, vegetation, water and air samples. Dose estimates based on environmental samples were in close agreement with calculated values and those measured by TLD's.

Iodine — Because iodine concentrates in the human thyroid gland, much effort was made to determine its presence in the environment. Both environmental samples and data collected at the meteorological station at TMI were used to determine its presence in the environment. It is estimated that between 15 to 30 curies of iodine-131 were released. A maximum thyroid dose of less than 20 millirems (0.02 rem) for any one person has been calculated. The total thyroid collective dose received by all people in the TMI area probably ranged from 1,400 to 2,800 person-rems.[22]

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Further, 762 people of the Three Mile Island area volunteered for whole body counting, a procedure that identifies and counts specific radionuclides in the body. None had body levels of iodine-131 above the minimum detectable activity of two billionths of a curie.[24] This amount of radioactive iodine would produce a dose of less than 12 millirems (0.012 rem). This further confirmed that iodine releases were very small and did not result in measurable radiation doses to the general population.

. . . 762 people of the Three Mile Island area volunteered for whole body counting. . . None had body levels of iodine-131 above the minimum detectable activity of two billionths of a curie.

For comparison, it should be noted that iodine-131 is used for a variety of diagnostic and treatment purposes in medicine. In a diagnostic medical thyroid scan, for example, patients receive an average dose of about 100,000 millirems (100 rems) to the thyroid gland.

Alpha-emitting Radionuclides and Particulates — Because alpha-emitting radionuclides pose special health concerns, scientists specifically monitored their presence in environmental samples. Of all the samples analyzed, not one demonstrated the presence of alpha radiation above that normally present in nature and those from previous atmospheric nuclear weapons testing. During the time of the accident, GPU and the EPA analyzed air and soil samples for alpha radionuclides. When these samples were compared to those from other regions of the United States, the results showed no difference in the amount of alpha radionuclides normally present.

Continuous air samplers monitor the amount of radioactivity in nearby communities. At the time of the accident, eight sampling stations monitored air samples for particulate radioactivity at various locations. None of the air samples showed radioactivity above normal background levels. In fact, DOE overflight surveys showed that the amount of radioactivity around TMI was no higher in 1982 than in years preceding the TMI-2 accident. Had significant amounts of particulate radionuclides been released, the 1982 survey would have shown increased levels. The radioactivity that was detected is normally found in the environment and is consistent with expected concentrations of naturally occurring radionuclides and radioactive fallout from past weapon tests.

. . . DOE overflight surveys showed that the amount of radioactivity around TMI was no higher in 1982 than in years preceding the TMI-2 accident.

Radiation Monitoring

Data from a network of 20 dosimeters around TMI provided the most reliable record of human radiation doses. Ten-year meteorological data and population demographic data were used to determine the optimum location for the TLD's. Collectively, the 20 stations provided data used in assessing radiation doses to the general public living in the Three Mile Island area.

During the accident, the GPU environmental dosimeters were augmented by independent TLD programs conducted by the EPA, HHS, and the NRC. Concerns have been raised about whether the GPU and NRC TLD's adequately measured various noble gases, about discrepancies between the NRC and GPU results, and about the possibility of gaps in recording radioactivity in areas between dosimeter stations (so-called "windows").

The concern raised about the TLD response to noble gas concentrations was in part valid. This issue was addressed and resolved by the President's Commission and the National Bureau of Standards. TLD's used by GPU and the NRC allowed small amounts of xenon gas to diffuse through the holders into the dosimeter. This caused the TLD's to record radiation levels greater than had actually occurred. In reality, people were exposed to less radiation than the TLD's actually recorded.

The discrepancies between exposures measured by GPU and the NRC can be explained by comparing the two sampling techniques. First, the NRC TLD's had received some radiation prior to placement in the field. They were further exposed to radiation during the transport from the NRC offices to the field station. Control TLD's were not used to subtract exposures obtained prior to actual field placement. The GPU TLD's were shielded during transport to and from the field station, and control TLD's were used to measure any radiation that may have been recorded prior to placement in the environment. Subsequent reviews by independent scientific investigative teams confirmed that the GPU TLD results were reliable and accurate for the calculation of radiation doses to the general public.

The possibility that "windows" existed was also addressed. Theoretically, larger amounts of radiation could pass between TLD stations than are measured by dosimeters at those stations. However, reliable meteorological data obtained during the TMI-2 accident show that, during periods when the highest releases occurred, the wind blew toward the monitoring stations rather than between them. Meteorological conditions that could have permitted large quantities of radioactivity to pass undetected between the TLD stations did not exist.

In addition, the exposure projection model used all available data, including existing meteorological conditions, plant monitoring data and dosimeter data to estimate the amount of radiation to which the general public was exposed. Exposures were calculated for all possible plume directions during the TMI-2 accident period and were used by other investigative groups. In general, exposures calculated from the TLD measurements compared favorably with those estimated from the amount of radiation actually released.[22,40]

Environmental Liquid Monitoring

Liquids released during the accident were monitored for radioactivity. In addition, GPU collected water samples from various locations upstream and downstream from the main discharge site to monitor for radionuclides. Estimates independently calculated by GPU, the NRC and various state agencies generally showed that the quantity of iodine-131 released in water was less than 0.3 curie. Radiation doses from these releases amounted to less than 1 millirem (0.001 rem) to the maximum exposed person and a collective dose of less than 1 person-rem for the entire population.[40]

Water and other aquatic samples collected at the time of the accident confirmed the radioactive releases to be small. Although iodine-131 was detected, it was found in samples collected both upstream and downstream from TMI, which indicated that it came from sources other than TMI. Area hospitals, for example, routinely administer iodine-131 to patients for diagnostic and therapeutic purposes, and this could eventually be discharged into the river. Analyses of river water samples in years following the TMI-2 accident and the shut-down of TMI-1 continued to show trace quantities of radioactive iodine upstream of the plant. Since iodine-131 ceases to be radioactive after a few weeks, its continued presence after years of reactor shut-down verified that the source could not be TMI.

GPU conducted a study to verify the reliability of the TMI liquid sampling stations and provided a mathematical model capable of estimating both downstream concentrations and travel times of the TMI effluent. This study tracked the dispersion and dilution of a dye from the TMI discharge point in 1980. When applied to the release estimates of the TMI-2 accident, the model predicted river water concentrations with a high degree of accuracy. The agreement between river samples and model predictions further supports the small release estimates based on station data.

Summary of Radiation Doses

GPU, the NRC and several independent investigative groups calculated the amount of radiation individuals and the general population were exposed to as a result of the TMI-2 accident.[22,27,38,40] There was general agreement that the primary exposure came from noble gases which are chemically and biologically unreactive. Exposure from noble gases was principally external in the form of gas traveling in the plume.* In calculating the maximum individual dose, the highest off-site TLD reading was used. The TLD at the east-northeast station, a distance of 0.5 mile, registered a cumulative dose of 83 millirems (0.083 rem).[22] This dose represented an upper limit to the general population for the period March 28 through April 7, 1979, since no member of the general public could have been closer to the plant. Individual and population dose levels were calculated from dosimeter and meteorological data and population distributions by distance from the TMI-2 nuclear power plant. The collective population dose was calculated by summing up each individual dose for the two million people living within a 50-mile radius of Three Mile Island. The radiation doses received by the general public can be summarized as follows:

Whole Body Dose Estimates to Individuals

- Highest dose to any one individual: less than 100 millirems (0.1 rem)
- Average dose to individuals living within a 10-mile radius of TMI: 8 millirems (0.008 rem)
- Average dose to individuals living within a 50-mile radius of TMI: 1.5 millirems (0.0015 rem)

Whole-Body Collective Population Dose Estimates

- Range: 1,600 to 5,300 person-rems to the general population living within a 50-mile radius
- Most probable estimate: 3,300 person-rems to the general population living within a 50-mile radius.

Thyroid Dose

- Highest possible dose: less than 20 millirems (0.02 rem) to an individual
- Average dose to individuals living within a 10-mile radius of TMI: less than 1 millirem (0.001 rem)
- Total collective population dose: 1,400 to 2,800 person-rems to the thyroid to the general population living within a 50-mile radius.

One way of evaluating the potential health impact of these whole-body doses is to compare them with the natural background radiation dose

*Radiation dose values for noble gases are whole-body doses and reflect the gamma radiation given off by noble gases. Noble gases also emit beta radiation which contributes dose to the skin. The skin dose in the absence of shielding (e.g., clothing) was approximately four times the whole-body dose.[22,38]

of 100 millirems (0.1 rem) per year. The average individual dose of 1.5 millirems (0.0015 rem) to an individual living within a 50-mile radius, therefore, would be equivalent to less than an additional five days exposure to natural background sources of radiation. Furthermore, the total collective dose from the accident to the two million population living within 50 miles would be less than one percent of the total radiation dose these people receive each year from medical and natural sources of radiation.

ASSESSMENT BY OTHER STUDIES OF RECORD

Within weeks of the TMI-2 accident, a number of federal and state investigations were begun to determine the causes of the accident and to assess the potential impact on the health and safety of the general population and the workers. Of primary concern was the need to determine radiation doses and possible health effects to individuals living in the TMI area. Radiation doses were based largely on ground-level measurements obtained by TLD's, aerial surveys by helicopter and samples of soil, grass, surface water and milk. The radiation doses to the general public were primarily due to the release of the radioactive gases krypton and xenon. Other radioactive products, such as iodine, were released in barely detectable quantities. Because the radioactive gases readily disperse into the atmosphere, exposure of people was transient and affected only those individuals in the path of the radioactive plume.

Section 4

Each of these investigative groups, after examining and analyzing all the available scientific data, issued comprehensive reports that are available to the public. The following summarizes the findings of the principal investigative reports:

Ad Hoc Population Dose Assessment Group[22]

Less than two months after the accident, an ad hoc group consisting of dosimetry experts from the NRC, the Department of Health and Human Services and the Environmental Protection Agency issued a preliminary report. The Ad Hoc Report concluded that the collective population dose within a 50-mile radius was 3,300 person-rems. This was based on an average of four separate estimates that ranged from 1,600 to 5,300 person-rems. The group estimated that the maximum exposure to any member of the public was less than 100 millirems (0.1 rem). These estimates were based on effluent, dosimeter, and milk and food data. The interagency group report concluded that there were no immediate health effects and that latent or long-term effects, if any, would be minimal.

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Nuclear Regulatory Commission

In April 1979, the NRC established its own investigative groups, which issued several reports.[22,23,25] Although health effects were not their main focus, detailed and well-supported operational and radiological sequences of events were provided, including population dose measurements.

The President's Commission[38]

President Jimmy Carter established an independent commission in April 1979 to investigate the TMI-2 accident. The Commission was directed to estimate the real and potential health effects to the general population and the workers.

". . . since the total amount of radioactivity released during the accident at TMI was so small . . . there may be no additional detectable cancers resulting from this radiation. . ."

The Commission's report concluded that ". . . since the total amount of radioactivity released during the accident at TMI was so small, and the total population exposed so limited (that), there may be no additional detectable cancers resulting from the radiation. In other words, if there are any additional cancer cases, the number will be so small that it will not be possible to demonstrate this excess or to distinguish these cases among the 541,000 persons (of the 2.2 million population) living within the fifty-mile radius of TMI, who would for other reasons develop cancer in their lifetime."

The Commission also stated that ". . . We conclude, therefore, that it is probable that there will be no detectable cases of genetically related ill-health . . . or abnormalities in newborn children resulting from the radiation exposure of the general public and pregnant women following the accident at Three Mile Island." The Commission's estimates of health effects were based on a collective population dose of 2,000 person-rems.

The President's Commission stated that the most important health effect of the accident was the mental stress experienced by the general population and the workers.

Governor's Commission[35]

". . . it is probable that there will be no detectable cases of genetically related ill-health. . ."

Governor Dick Thornburgh of Pennsylvania established a commission in May 1979 to study and evaluate the TMI accident and its consequences. The Governor's Commission accepted the radiation exposure estimates made by the Ad Hoc Interagency Exposure Assessment Group.[22] It also agreed with the findings of the President's Commission, which concluded that the radiation releases would have negligible health effects. The only health effect noted by the Governor's Commission was that of mental stress. The Commission concluded that this health effect would be transient for the general population.

Report to the NRC Commissioners and to the Public (The "Rogovin" Report)[27]

Recognizing the potential conflict of interest involved if the inquiry of the TMI accident was directed and undertaken solely by its staff, the NRC asked the law firm, Rogovin, Stern & Huge, to conduct an impartial inquiry into the TMI-2 accident. Neither the law firm nor any of its affiliated members had any previous involvement with the NRC or the nuclear industry. They concluded the following:

- Despite the uncertainties in the off-site dosimeter data, it was adequate to characterize the magnitude of the collective exposure to the population.

- The collective exposure was within the ranges estimated by the Ad Hoc Interagency Exposure Assessment Group and the Task Group of the President's Commission. Correcting for occupancy factors, shielding and reductions in the population due to voluntary evacuation, the population exposure was probably in the lower end of those ranges, about 2,000 person-rems.
- The maximum off-site individual exposure was less than 100 millirems (0.1 rem).
- The contribution of internal exposure to the population was small compared to the exposure from external irradiation.
- It was extremely unlikely that anyone would suffer discernible ill effects during his or her lifetime from radiation exposure associated with the TMI-2 accident. The effects on the population as a whole, if they existed at all, would certainly be nonmeasurable and nondetecable.

Predicted Acute Health Effects

Based on field measurements of radiation doses to the public and the current scientific understanding of the relationship between health effects and radiation dose, the reports issued by the different investigative teams and groups included predictions of how the TMI-2 accident might affect the health of the general population. The minimum radiation dose required for any observable acute health effect would be approximately 100,000 millirems (100 rems) to the whole body. This minimum dose would still be about one thousand times greater than the maximum individual dose of 100 millirems (0.1 rem) that could have been received by an individual as a result of the TMI accident. Consequently, no individual in the TMI area could have experienced any acute effects from exposure to radiation released during the TMI accident.

. . . no individual in the TMI area could have experienced any acute effects from exposure to radiation released during the TMI accident.

Predicted Delayed or Late Health Effects

The various commissions and investigative groups established that the collective dose or population exposure, which is the sum of all exposures for the two million individuals living within 50 miles, fell within the range of 1,600 to 5,300 person-rems. This population is exposed to 200,000 person-rems each year from natural radiation and an additional 200,000 person-rems from medical and other sources of radiation each year.

Cancer and genetic effects among individuals occur with relatively high frequency in the normal population. Table 7 shows the number of cancers that would be expected to occur spontaneously and additional cases that might potentially be induced by radiation from the TMI-2 accident. These latter estimates are based on currrent knowledge of the health effects of radiation (lifetime risk of approximately 3 additional cancers per 10,000 persons each exposed to 1,000 millirems or 1 rem).

Table 7

Potential Radiation Health Effects of the TMI-2 Accident to the 2 Million Population Living Within 50 Miles[22]

	Naturally-Occurring Health Effects	Potential Health Effects from the TMI-2 Accident
Total Cancers	541,000	1
Fatal Cancers	325,000	less than 1
Nonfatal Cancers	216,000	less than 1
Genetic Effects	78,000	less than 1

The prediction of one excess cancer is a calculated value which is based on the collective population dose of 3,300 person-rems. If such an effect does appear, it will not be detectable above the 541,000 naturally occurring cancers in the two million residents of the TMI area. It is unlikely that any health effects will ever be observed due to the radiation released from the TMI-2 accident. Nevertheless, in spite of the predicted absence of measurable health effects, a number of human health and other studies has been undertaken in the TMI area to determine whether any health effects could be detected.

TMI-2 HEALTH STUDIES

Within months after the accident, the Pennsylvania Department of Health initiated several epidemiological studies to evaluate the possible long-term health effects of the TMI-2 accident. Of particular concern were pregnancy outcomes, infant health and cancer. The studies focused on people who lived in the immediate area of TMI.

One of the first steps was to develop a TMI population registry. In all, data were collected for the 35,000 persons living in the immediate area of TMI. Data included information on age, race, residence, marital status, smoking habits, pregnancy history, medical history, previous medical and occupational radiation exposure, and a detailed accounting of time and whereabouts during the accident and the 10 days following. This TMI population registry provides pertinent information for future epidemiological studies. Some of these studies have been completed while others are still in progress and, in some cases, will continue for many years.

PENNSYLVANIA DEPARTMENT OF HEALTH STUDIES

The following is a brief summary of findings of the epidemiological studies performed by the Pennsylvania Department of Health.[33a,33b]

Pregnancy outcome

A total of 3,582 pregnant women who delivered within one year following the TMI accident and who had lived within 10 miles of TMI at the time of the accident were compared with a control group of 4,000 pregnant women who were not exposed. Studies of the population exposed in-utero during the accident showed no measurable differences for prematurity, congenital abnormalities, neonatal deaths or any other factors examined. This "TMI Mother-Child Registry" will continue to follow the children and issue reports at five-year intervals on any physical, psychological and behavioral effects.

Infant hypothyroidism

Radioactive iodine, when accumulated in sufficient quantities in the fetal thyroid, has the potential for producing infant hypothyroidism. Of approximately 4,000 infants born within one year of the accident, only one case of infant hypothyroidism was reported within a 10-mile radius of TMI, which is well within the range of expectation for a normal group of infants of this number.

Seven cases of congenital hypothyroidism were reported in Lancaster County, which is outside the 10-mile radius of investigation. After detailed analyses of these cases, the Pennsylvania Department of Health concluded that these ". . . cases of congenital hypothyroidism were not related to the TMI nuclear accident." It further concluded that ". . . these types of anomalies are not expected to result from direct or indirect exposure of the fetus to radiation. This conclusion was also supported by an independent Hypothyroidism Investigative Committee organized by the State Health Department which included expertise in the fields of epidemiology, pediatric endocrinology, obstetrics, medical genetics, biostatistics, and radiation physics."[33a]

Infant Mortality

No significant differences were found in infant mortality rates within a 10-mile radius of TMI when compared with study groups living in other areas of Pennsylvania and when compared with infant mortality rates for previous years.

Psychological Effects (Stress) and Mental Health[8,38]

Several studies dealing with psychological stress were conducted within months of the TMI-2 accident, including the President's Commission and the Pennsylvania Department of Health. This latter study showed elevated stress levels near TMI that persisted into 1980. Stress primarily took the form of demoralization and mental stress. Those who were most likely to experience stress were young, well-educated, married women who lived within 15 miles of TMI and who were mothers of young children.

TMI Cancer Study

In September, 1985, the Pennsylvania Department of Health issued a report of a cancer study performed around TMI.[33b] The purpose of the study was to determine if there was evidence of excess cancer cases or cancer deaths. It also sought to determine if the findings were consistent with past studies of cancer and current understanding of cancer induction by radiation.

Method of Study — A common approach in epidemiological research is to compare the observed incidence of cancers with those expected normally in two comparable populations. Any statistical difference between observed and expected cancers can provide indirect evidence for the existence of a cancer-causing agent.

The Pennsylvania Department of Health regularly records cancer mortality for each of the 2,580 communities within the state. Since the 1979 TMI accident, the 35 communities within 10 miles of TMI have undergone more intensive monitoring. Because of the potential importance of wind direction and radioactive plume dispersion during the first days after the accident, particular attention has been given to four communities surrounding the TMI facility; i.e., Fairview and Newberry Townships, and Goldsboro and York Haven Boroughs.

Data used in determining cancer deaths and incidence were obtained from several sources including the Pennsylvania Department of Health, which maintains vital statistics on cancer by age, sex, race, anatomical site and residency.

The number of cancer deaths expected in the general population was based on data collected by the Pennsylvania Department of Health for the years 1979-1981. The data was categorized by age, sex, and specific population for eight major cancer categories. Similarly, the expected number of new cancer cases was based on incidence data by cancer site, age and sex from the Surveillance, Epidemiology and End Results (SEER) program (1978-1981) of the National Cancer Institute (NCI) and Pennsylvania and United States population data from the 1980 census.

Results of Cancer Mortality Study — The Department of Health study has shown that, to date, there has been no evidence that the number of cancer deaths in the TMI area has been different than that which would have been expected. The 2,892 cancer deaths that occurred within a 10-mile radius of TMI were nearly identical in number to the 2,909 cases statistically predicted for the five-year period following the TMI-2 accident. Similarly, for a 20-mile radius, 7,924 cancer deaths were recorded where 8,177 would have been predicted for that same period.

. . . to date, there has been no evidence that the number of cancer deaths in the TMI area has been different than that which would have been expected.

Analysis of data for smaller geographical areas also showed no significant differences from expected values. The four down wind communities representing approximately 25,000 residents had 144 cancer deaths, similar to the 142 cases that were expected. Further, when the cancer mortality statistics were analyzed by cancer type, including leukemia, there were no significant differences between observed and expected numbers of cancers according to type. Since these very small differences are due to normal statistical variation, it cannot be concluded that the radiation released during the TMI accident increased the incidence of cancer in the general population.

Results of Cancer Morbidity Study — Analysis of the number of newly diagnosed cases of cancer also showed no difference between observed and expected cases. This includes those cancers that might normally have been expected as a consequence of large radiation doses. In particular, leukemia, the most likely cancer that could have been detected as early as five years following exposure to radiation, was diagnosed in only two individuals, while four cases were expected among residents of the four down wind communities in the absence of excess radiation.

Cancer incidence was examined among 3,582 pregnant women and their children who were born within one year following the TMI-2 accident and who lived within 10 miles of TMI. Based on the national cancer registry data for women age 10 to 44, 3.9 mothers might have been expected to be diagnosed with cancer, which is the same as the four cases observed. Among their children, two have been diagnosed with cancer, while one case would have been predicted. Thus, available information based on mothers and their children who may have been exposed during the accident provided no indication of a statistically significant increase in cancer for either group.

Conclusion — The Pennsylvania Department of Health, after studying cancers among residents within 20 miles of TMI, concluded that the ". . . results of our epidemiologic study including both mortality and morbidity data as well as cohort follow-up analysis do not provide evidence of increased cancer risks to residents near the TMI nuclear plant."[33b] Since

". . . results of our epidemiologic study . . . do not provide evidence of increased cancer risks to residents near the TMI nuclear plant."

the latency period between exposure to a cancer-causing agent and the development of cancer may extend for many years, the Pennsylvania Department of Health will continue epidemiological studies of health effects, including cancer.

REPORTS OF ACUTE HEALTH EFFECTS

Although these Pennsylvania and other governmental health studies have not shown any adverse health effects resulting from the accident, a number of residents living around TMI have claimed both acute and delayed or late health effects did occur. The following list identifies acute health effects that have been most frequently claimed during and following the TMI-2 accident.

- Metallic taste or odor
- Disruption of menstrual cycle in women
- Burning watery eyes
- Respiratory inflammation
- Skin reddening (erythema) and skin disorders
- Nausea and vomiting
- Diarrhea and rectal bleeding
- Organ collapse
- Heart dysfunction (tachycardia and aortic valve defect)

Metallic Taste

By far the most frequently cited effect by some TMI area residents was that of a metallic taste or odor occurring at the time of the accident. No scientific evidence exists, however, that identifies radiation as a cause for a metallic taste or odor. Some people have suggested that iodine released by the TMI-2 accident may have been the cause. Yet, while reports of metallic taste coincide with the early days of the accident, some people have reported this sensation occurring both before and years after the accident.

Iodine can induce a metallic taste when administered as a medicine. The total 15 to 30 curies of iodine-131 released during the accident corresponds to 0.1 to 0.2 milligram of iodine dispersed into the atmosphere. If this amount were dispersed instantly into the environment, there would be less than 0.0004 milligram per cubic meter of air at the boundary of the TMI nuclear plant site. As distance from the site increases, the concentrations would continue to decrease by many orders of magnitude. This amount of iodine is extremely small compared with iodine taken as a nutritional supplement in kelp tablets (0.1 milligram each), or when iodine is prescribed medically as an expectorant in quantities of about 300 milligrams per dose.

For the metallic taste and odor at distances of several miles to have been caused by iodine in the environment, massive releases involving millions of curies would have had to occur. The minute quantity of less than 1 milligram of radioactive iodine released during the several-day period of the accident could not be the cause of a metallic taste.

Many foods, drugs and industrial chemicals are known to cause a metallic taste. "Hazard Line", an information service that provides data on more than 77,000 industrial substances, lists more than 200 chemicals that can cause a metallic taste. Many are commonly used in the automobile, steel, foundry, plating, chemical, mining and battery manufacturing industries. Several of these industries are located in the general Harrisburg area. A brief review also identified 14 pharmaceutical drugs that are known to induce a metallic taste.

The mineral selenium also causes a metallic taste. Farmers in the Etters, Pennsylvania area have stated that there is a selenium deficiency in the crops grown for animal feed. As a result, some people supplement their own diets with selenium. Selenium may be the source of a metallic taste in those individuals.

Disruption of Menstrual Cycle

Women exposed to doses of about 200,000 millirems (200 rems) may experience temporary disruption of their menstrual cycle. The scientific evidence clearly shows that menstrual disruption is not linked to radiation doses like those associated with the TMI-2 accident. Many factors are known to alter the regularity of the female menstrual cycle, including hormonal, dietary and psychological factors.

Burning and Watery Eyes

Radiation can affect the eyes, but only at extremely high levels of exposure. For example, therapeutic radiation exposure of 6,000,000 to 7,000,000 millirems (6,000 to 7,000 rems) can irritate the eyes, cause conjunctivitis (an inflammation of the inner linings), and cause increased sensitivity to light. However, exposures of this magnitude would also produce severe skin changes and, for penetrating radiation, would be lethal if delivered to the whole body. On the other hand, common factors known to cause irritation of the eyes include eye infections, allergies and chemical irritants.

Respiratory Inflammation

A few persons have complained that they had trouble breathing soon after the accident. Radiation can cause a respiratory inflammation but only for exposures well above 200,000 millirems (200 rems) and only after several weeks following exposure. Thus, the scientific evidence clearly shows that the alleged breathing problems were not caused by radiation from the TMI-2 accident. Other causes of respiratory inflammation include infection, allergies and chemical irritants.

Skin Effects

Reports of skin disorders included skin reddening (erythema), blistering, rashes, loss of hair and ulceration. Erythema and hair loss require doses of 300,000 millirems (300 rems) or more. Other skin disorders require exposures in excess of 1,000,000 millirems (1,000 rems). Many of these disorders are similar to allergic responses to sunlight, drugs, chemicals, cosmetics, other physical agents and the normal aging processes.

Nausea and Vomiting

Several people reported feeling nauseous after the TMI-2 accident. Usually, however, people must be exposed to radiation doses greater than 100,000 millirems (100 rems) to experience nausea and vomiting. These common symptoms can also be induced by bacteria and viral infections, alcohol, motion, food allergies and emotional stress, among others.

Diarrhea and Rectal Bleeding

Diarrhea and rectal bleeding are symptoms of severe gastrointestinal tract injuries usually experienced only after radiation doses of more than 500,000 millirems (500 rems). These doses, when delivered to the whole body, cause injuries which usually result in death. However, diarrhea is a common response to indigestion, certain irritant foods, allergies, or infection. Similarly, rectal bleeding is a common symptom and may be the result of hemorrhoids or localized tissue injury due to constipation.

Organ Rupture or Collapse

Several TMI area residents have reported collapsed or ruptured lungs, spleens, kidneys and hearts. These are rarely observed radiation injuries. Exposure to several million millirems (several thousand rems) of radiation would be required to produce such situations. If the source of radiation were external, this would imply whole-body exposures, which would have been lethal. Some people have suggested that the source of radiation was internal to the body through uptake of radioactive cesium released by TMI-2. Cesium, like potassium, is taken up by body cells, with muscle accounting for some 80 percent of the total.

Table 6, which includes an analysis of airborne effluent data, reveals that 0.00001 and 0.00004 curie, respectively, of cesium-134 and cesium-137 were released during the accident. Even if someone inhaled or ingested all the released cesium, the whole-body exposure would have been less than 3,000 millirems (3 rems). More than 1,000 times this dose would be required for even one person to have suffered organ damage. The major causes of ruptured or collapsed organs are due to severe trauma to the body from accidents or injury associated with diseases unrelated to radiation.

Heart Dysfunction (Tachycardia and Aortic Valve Defect)

The heart consists primarily of muscle tissue. Overall, the heart is highly resistant to radiation; the estimated exposure required to destroy heart functions is about 10,000,000 millirems (10,000 rems). Acute exposures for cancer patients undergoing radiation treatment in excess of 1,000,000 millirems (1,000 rems) can result in minor heart dysfunction. Tachycardia (rapid pulse) is commonly a response to stressful situations, such as fright, emotional upset, fever, congestive heart failure and hypotension. It is estimated that up to two percent of the population suffers to some degree from cardiac defect involving the aortic valve. The most common causes include congenital malformation and streptococcal infection leading to rheumatic heart disease.

Summary and Conclusions of Acute Health Effects

Because ionizing radiation in sufficient doses may affect most human cells, health effects can cover a wide range of disorders characterized by a broad range of clinical signs and symptoms. The probability and severity of acute health effects soon after exposure are dependent, in large measure, on the radiation dose and the rate of its delivery. On the other hand, a lengthy list of agents and diseases can singly or in combination cause symptoms that are similar to those claimed by a number of people during the accident. Given the high radiation doses required to cause some of those signs and symptoms and the low radiation doses these people were actually exposed to during and following the TMI-2 accident, it can only be concluded that these symptoms were not caused by radiation exposure from the TMI-2 accident. In summary:

- The evidence compels the conclusion that the radiation doses were not sufficient to induce any acute health effects in the exposed population. Dosimetry and environmental sampling data indicate doses thousands of times lower than those required for the reported health effects.
- Some of the acute health effects claimed are never associated with radiation at any dose levels.
- The time of onset, duration and sequence of health effects claimed are not associated with the clinical course of the acute radiation syndrome in man.
- Most of the reported acute health effects, if due to radiation, would have required exposures to doses that would have been fatal to those affected.
- For damage to have been caused by ingestion or inhalation of radionuclides, the associated health effects would require concentrations of radioactivity millions of times greater than those actually determined from the thousands of environmental samples analyzed after the accident.

Dosimetry and environmental sampling data indicate doses thousands of times lower than those required for the reported health effects.

REPORTS OF EFFECTS ON VEGETATION AND ANIMALS

A few local residents have claimed that radiation releases from the TMI accident caused abnormal growth of plants and vegetables. They cite a failure of trees to produce fruit, a lack of honey bees to pollenate clover, defoliation of trees, abnormal stem and leaf growth, and even death of some plants. In light of the radiation doses and dose rates observed during the accident, the occurrence of such radiation-associated effects would not be consistent with our extensive knowledge of the responses of complex biological systems such as humans, animals and plants. As a rule, the more biologically complex the organism, the more sensitive it is to radiation. Whole-body doses of 400,000 to 500,000 millirems (400 to 500 rems) are fatal to most people, yet some lower forms of life may suffer only minor biological effects from exposures of 1,000,000 millirems

Some of the acute health effects claimed are never associated with radiation at any dose levels.

(1,000 rems) and more. Radiation doses sufficiently large to kill insects or plants would have killed thousands of humans within hours, days or within a few weeks of the accident. This did not occur.

Abnormal growth of vegetation was alleged to be caused by radioactive calcium, phosphorus, and zinc. Although plants use these elements, the radioactive releases from TMI could not be the cause. These radionuclides accumulate in sizeable quantities only after years of reactor operation and are retained in the reactor core. The TMI-2 reactor had only been in use for three months at the time of the accident. Presently, 90 percent of these radionuclides are still in the reactor vessel (approximately five percent have decayed and another five percent have been removed through various cleanup procedures).

There was no evidence of release of these radionuclides to the atmosphere at the time of the accident. A release of these radionuclides sufficiently high to cause damage to vegetation would have been detected in water and air samples; none were detected.

It is important to note that plants in the springtime use nutrients which were stored in plant tissues from the previous growing season. Thus, it would have been nutrients stored since 1978 that would have been used in the spring of 1979; i.e., non-radioactive nutrients taken up some time prior to the accident.

Several state and federal agencies, including the Pennsylvania Department of Agriculture and the U.S. Environmental Protection Agency, investigated all claims of abnormal plant and animal effects occurring at the time and soon following the TMI-2 accident. They were unable to verify any form of radiation damage, attributing most reported cases to natural causes or animal feeding problems.[26] Infrared photography and ground surveys conducted in the TMI area from 1977-1980 as part of an environmental monitoring program also failed to identify unusual damage to vegetation. These surveys did find evidence of plant damage caused by anthracnose (a fungus infection) and locust leaf miner (a small beetle). The studies concluded that these conditions were not unusual and were not related to any radiation released by the TMI accident.[28,29,30,31]

Questions have also been raised concerning the failure of honey bees to maintain a clover seed yield. The U.S. Department of Agriculture (USDA) monitors unusual bee mortality. Only two known cases of unusual bee mortality have been reported in the vicinity of TMI in recent years; one occurred in the late 1970s near Mechanicsburg and a more recent case occurred near Chambersburg.[34] However, both situations resulted from the overuse of pesticides. The use of extensive pesticides in the TMI area could have had similar consequences. The USDA further explained that bees have little effect on clover yields since most Pennsylvania farmers harvest clover before it goes to seed. It is common practice among local farmers to grow clover from commercial seed preparations.

Allegations concerning unusual health effects in various farm and domestic animals due to the radiation released during the TMI-2 accident were reported in the media. The NRC has investigated these reports and found that, "No reasonable connection could be made between the problems of livestock and pets that were brought to the attention of the staff of the Nuclear Regulatory Commission. . . . The most likely causes of the reported animal husbandry problems are nutritional deficiencies and infectious diseases, as indicated by disease symptoms as well as by the improved health of livestock that were given feed supplements."[26]

In addition, the Pennsylvania Department of Agriculture records show that yield per acre from 1976 through 1982 for the counties surrounding TMI for wheat, barley, oats, hay and apples were relatively consistent for all years.[4] Potato and corn yields were lower in 1980 than other years and peach yields were lower in 1981, but these declines probably reflected the drought conditions of 1980-1981. These results support the conclusions contained in the official assessment reports. Field samples taken during the accident and harvest yields all indicate that the small doses of radiation were not the source of plant and animal anomalies.

CANCER SURVEY CONDUCTED BY LOCAL RESIDENTS

Perhaps the most publicized and controversial report of human health effects involved a cancer survey conducted by the Aamodts, two former local residents of the Three Mile Island area. The Aamodts initially made their results public in June 1984 in the form of a petition to the NRC.[1a] At the request of the NRC, this report was reviewed by the Center for Disease Control (CDC) of the U.S. Public Health Service. CDC physicians and scientists concluded that the Aamodts' cancer survey contained a "number of deficiencies" and failed to present evidence of an increased number of cancer cases or cancer deaths among TMI-area residents.[14]

In November 1984, the Division of Epidemiology Research of the Pennsylvania Department of Health was requested to analyze the Aamodts' cancer survey data. In a report subsequently issued by the Pennsylvania Department of Health, Dr. George Tokuhata of the Division identified serious flaws in the Aamodts' cancer survey, including deficiencies in the methodology and design of the survey, and errors and faulty interpretations.[33b]

In January 1985, the Aamodts filed a motion with the NRC which contained more detailed information on their health effects survey (this information provided verification of their data which the Aamodts had requested of the NRC in their June 21, 1984 motion [1b]).

Deficiencies in Methodology and Design

In the Aamodts' study, volunteer citizens conducted door-to-door surveys in three small rural communities where residents had reported "adverse health effects". The three survey areas consisted of 35, 93 and 15 households and represented 457 people. For the five years following the

TMI-2 accident, the study claimed the small population in question suffered death rates from cancer 5.2 to 6.5 times higher than expected.[1a]

Radioepidemiological studies are designed so that the study group surveyed differs from a control group used for comparison in that the survey group had been exposed to radiation and the control group had not. Survey data must be collected without bias and individuals in the survey group must be carefully matched with individuals of the control group with respect to age, sex, occupation, smoking habits, and other risk factors.

Because of extensive media coverage since the accident, not only the volunteers but the individuals interviewed may have assumed that any medical or health problem that they may have experienced during this time was related to the radioactive releases during the TMI-2 accident. Consequently, interviewers and those being questioned may have responded in a way that would support such a bias. The questions used in the survey also could have suggested certain responses.

The three areas surveyed are located within York County. Survey Area 1, 4.5 to 6 miles northwest of TMI, consists primarily of houses along a single rural road. Survey Area 3, about 7 miles north-northwest of TMI, likewise consists of a single road. Based on official census data, the Pennsylvania Department of Health identified errors in the survey data with respect to the number of households and residents for Areas 1 and 3.

However, the most serious bias in data acquisition was uncovered in Survey Area 2 (Newberry Township). Specifically, Area 2 is represented by 14 streets that collectively should have been surveyed. Instead, only four streets were selected and, whereas at least one cancer death was confirmed on each of the four selected streets, the Department of Health did not identify any cancer deaths during the period of the study on the 10 streets that had been excluded.

Errors and Faulty Assumptions

The Pennsylvania Department of Health, in reviewing death certificates and medical records, identified a number of errors in the Aamodt survey:

- **Inclusion of extra cancer deaths** – While the survey identified four cancer deaths in Area 3, only two could be confirmed (one individual was apparently confused with a relative who died; another individual was not a resident at the time of the TMI-2 accident).

- **Failure to adjust for age-sex in computing expected cancer mortality** – The survey failed to take into account either the age or sex distribution of the individuals surveyed. This ignored the fact that cancer deaths are affected by sex and increase with age. Thus, if the age and sex distribution of the population under study differed from that of the comparison group, the calculated number of cancer deaths expected would be in error; this was the case in the Aamodt's survey.

- **Inclusion of cancer deaths diagnosed prior to the TMI-2 accident**– Of the 20 cancer deaths identified by the survey, six cases were medically diagnosed as having cancer before the 1979 accident. In one case, the cancer was diagnosed in 1969, 10 years before the accident.
- **Failure to adjust for confounding risk factors** - Although lung cancer occurs among nonsmokers, there is a staggering increase in lung cancer rates among smokers. Both lung cancer deaths in the survey involved individuals who were long-term heavy smokers.
- **Faulty interpretations** - An insufficient period of time had elapsed since the accident to justify any association between the observed cancers and the radiation from the TMI-2 accident. For high radiation doses, the minimum latency period for leukemia is about two years and for most solid cancers this minimal latency period is 10 years.[12] Furthermore, following early diagnosis, cancer patients may continue to live for years or even decades with proper medical treatment. Thus, cancer deaths reported in the Aamodt survey, excluding leukemia deaths, could not have occurred so soon after the TMI-2 accident to be associated in any way with radiation released at the time of the accident.

. . . cancer deaths reported in the Aamodt survey, excluding leukemia, could not have occurred so soon after the TMI-2 accident to be associated in any way with radiation released at the time of the accident.

CONCLUSION

The Pennsylvania Department of Health, in its evaluation of the Aamodts' survey, stated:[33b]

> "While the authors of this small area survey claimed that cancer mortality has markedly increased around TMI, and implicated the 1979 nuclear accident at TMI as being responsible, the data presented in their survey do not support their conclusions . . ."
>
> " . . . the comprehensive epidemiologic studies conducted by the Pennsylvania Department of Health do not provide evidence that cancer mortality has increased significantly around TMI."

In addition, the U.S. Supreme Court has twice dismissed the Aamodts' contentions of health effects from the TMI-2 accident.

The various reports and claims of acute (early) and delayed (late) biological and health effects in the human populations, animals, and plants during and following the accident at TMI were carefully and extensively examined by appropriate federal and state agencies. The scientific evidence and analyses failed to support any radiation-related biological or health effects claimed to have occurred following the releases of low-level radioactivity at the time of the accident. In particular, the human cancer survey carried out by TMI-area residents had serious methodological flaws; the epidemiological analysis by the Pennsylvania Department of Health demonstrated convincingly that no excess of cancer cases has occurred in the TMI area since the TMI-2 accident in 1979.

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GLOSSARY

Activation products - Materials that become radioactive when bombarded by the neutrons released during fission.

Alpha-emitting radionuclide - A radioactive element which emits alpha radiation.

Alpha radiation - Consists of positively charged particles. Alpha radiation will be stopped by the outer layer of skin; it can be stopped completely by a sheet of paper. However, the potential hazard from alpha-emitting materials is due to the possibility of internal deposition to the body by ingestion or inhalation.

Beta radiation - Beta particles are similar to electrons, but originate in the nucleus of the atom. Beta is more penetrating than alpha radiation and can pass through 0.5-1 centimeter of water or human flesh. A sheet of aluminum a few millimeters thick can stop beta radiation. There is also an inhalation hazard from beta radiation.

Curie - A measure of radiation named after Marie Curie, the discoverer of radium. A curie represents a decay rate among fission products of 37 billion radiation emissions a second. Because of the extremely small amounts of radioactive material in the environment, it is often more convenient to use fractions of a curie; e.g., subunits like millicurie (one thousandth of a curie) or microcurie (one millionth of a curie) or even picocurie (one trillionth of a curie).

Dose - The quantity of radiation absorbed (units, rad or rem).

Effluent (radiological) - Release of radionuclides originating from the reactor vessel into the environment.

Exposure (radiation) - A quantity of radiation measured in air.

Fission products - Elements or compounds that result from nuclear fission and may be radioactive.

Gamma radiation - Consists of photons (wave energy) that can be very penetrating. Depending on the energy levels, gamma radiation can pass through the body. Dense materials such as concrete and lead are used for shielding against gamma radiation.

Genetic effect - An effect occurring in the germ cells of the irradiated individual that is passed on through biological mechanisms of inheritance to the descendants of a parent.

Half-life - That time for a radioactive nuclide to lose one-half of its activity. Each radionuclide has a characteristic half-life which can range from less than one second to years.

Isotope - Any of two or more species of atoms of a chemical element with the same atomic number (number of protons in the nucleus), but with different atomic mass and different physical properties.

Latency period - A period of seeming inactivity between the time of exposure of tissue to an injurious agent and appearance of a response.

GLOSSARY (Continued)

Low-LET Radiation - Radiation like x-rays, gamma rays, and beta particles which produce a spatially sparse distribution of ions.

Natural radiation - Occurs naturally from materials in the earth's crust, cosmic rays and other sources. Natural radiation dose rate to human beings living in the Harrisburg area, excluding medical radiation, is about 100 millirems (0.1 rem) a year. Natural background radiation increases with distance above sea level. It is, for example, about twice as high in Denver as in Harrisburg.

Noble gas - A gas that is chemically and biologically nonreactive, e.g., xenon and krypton.

Particulates - Microscopic particles that may be radioactive.

Person-rem (synonym, man-rem) - Person-rem is a unit that measures collective population dose. It is calculated by multiplying the number of persons exposed times their average individual dose in rems.

Radiation - Radiation is energy in the form of waves or particles that can penetrate matter. Although the term "radiation" includes such things as light and radio waves, it is most often used to mean "ionizing" radiation, which can produce charged particles ("ions") in materials it strikes.

Radioactivity - A process by which unstable atoms of an element emit or radiate the excess energy of their nuclei and change (or decay) to atoms of a different element or to a lower energy form of the original element. Radiation energy differs according to the isotope and the atomic makeup of elements involved.

Radionuclide - A radioactive atomic species of an element.

Rem - The unit of radiation dose-equivalent to the human body. Since human exposure to radiation usually involves very small exposures, smaller units are used; namely, millirem (1/1000th of a rem). The rem and rad (millirem, millirad) are used interchangeably for beta, gamma and x-ray radiation.

Somatic effect - An effect that may manifest in the body of the exposed individual over his or her lifetime.

Thermoluminescent Dosimeter (TLD) - A device that is commonly used to measure radiation exposure for personnel as well as for environmental monitoring. Sometimes simply called a dosimeter.

Transuranics - A group of elements that are produced by neutron transformation of uranium.